Quality Research, Development, and Consulting Inc.

Smart Screening System (S3)

In Taconite Processing

Semi Annual Report

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Semi Annual Report

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ABSTRACT

The conventional screening machines used in processing plants have had undesirable high noise and vibration levels. They also have had unsatisfactorily low screening efficiency, high energy consumption, high maintenance cost, low productivity, and poor worker safety. These conventional vibrating machines have been used in almost every processing plant. Most of the current material separation technology uses heavy and inefficient electric motors with an unbalanced rotating mass to generate the shaking. In addition to being excessively noisy, inefficient, and high-maintenance, these vibrating machines are often the bottleneck in the entire process. Furthermore, these motors, along with the vibrating machines and supporting structure, shake other machines and structures in the vicinity. The latter increases maintenance costs while reducing worker health and safety.

The conventional vibrating fine screens at taconite processing plants have had the same problems as those listed above. This has resulted in lower screening efficiency, higher energy and maintenance cost, and lower productivity and workers safety concerns. The focus of this work is on the design of a high performance screening machine suitable for taconite processing plants.

SmartScreens™ technology uses miniaturized motors, based on smart materials, to generate the shaking. The underlying technologies are Energy Flow Control™ and Vibration Control by Confinement™. These concepts are used to direct energy flow and confine energy efficiently and effectively to the screen function. The SmartScreens™ technology addresses problems related to noise and vibration, screening efficiency, productivity, and maintenance cost and worker safety. Successful development of SmartScreens™ technology will bring drastic changes to the screening and physical separation industry.

The final designs for key components of the SmartScreens™ have been developed. The key components include smart motor and associated electronics, resonators, and supporting structural elements. It is shown that the smart motors have an acceptable life and performance. Resonator (or motion amplifier) designs are selected based on the final system requirement and vibration characteristics. All the components for a fully functional prototype are fabricated. The development program is on schedule.

The last semi-annual report described the need and the work accomplished to design a supporting structure. The modified supporting structure design improved system rigidity and integrity and helped improve overall system performance. Lab test results showed a significant improvement in reducing undesired supporting structure vibration, better system performance and ease of installation. However the system performance suffered severe losses due to installation requirement.

Since then significant work was completed both in terms of analysis and experimentation to minimize system installation sensitivity and to relax plant structure foundation requirement. Lab test on the modified system are near completion and we plan to test the system in field in early next quarter. With the assistance of Albany Research center, strain measurements were successfully completed on the S3i-101 unit.

This report also includes the work initiated to investigate feasibility of inserting **SmartScreens™** technology in the field of dry applications.

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INTRODUCTION

Current screening machines have one thing in common: they operate using an electrical motor with a rotating unbalanced mass to generate shaking. Based on the information from Minntac Grant Application [1], Minntac has struggled with finding engineering solutions for noise and vibration problems caused by conventional screening machines. Evaluations of isolation curtains/walls, different screening machine brands, and lower speeds have resulted in minimal improvements in noise levels and have significantly compromised production. Blinding of screens is another major cause for loss in production. Minntac has estimated that approximately 2494 megawatt hours per year alone are lost due to poor screening recovery and wasted energy.

The ultimate goal of this project is to develop SmartScreens™ that will replace the inefficient massive electric motors. SmartScreens™ will have miniaturized smart motors (ceramic- or electromagnet-based). SmartScreens™ will incorporate an energy management technique to control energy flow and will confine injected shaking energy to the screen panels. In 2002, the QRDC team proposed to combine state-of-the-art smart materials, the concept of single or multi-stage resonators, and the patented energy management technique. This innovative technology has won several Research and Development awards from the U.S. Army, Navy, and Air Force and commercial organizations [2-6].

In the previous reporting periods, it was shown through computer simulations and laboratory prototypes that smart motors, accompanied by specially designed resonators, meet current screening vibration levels while simultaneously significantly reducing power consumption and energy loss. The ceramic materials and electromagnetic drives used in these motors are well suited for applying large dynamic forces and the required shaking functions to resonators. The smart motors consume 50% to 96% less energy than the bulky electrical motors, and are capable of operating over a wide range of frequencies. They are almost maintenance free, as they do not have any moving components and do not need lubrication. Additionally, smart materials (such as PZT) can function as both collocated sensors and actuators for active control of the shaking action and process automation.

In the first semi-annual report [7], it was shown that cantilever resonators of appropriate shape and size could be used to amplify the displacements and accelerations of the miniaturized ceramic motors so that the screening function was optimized. Finally, it was shown through simulations that the system can be optimized and completed by incorporating the energy management techniques that have been developed by QRDC. Energy management is composed of energy diversion, confinement, dissipation, conversion, and cancellation. It is the combination of smart materials and these vibration energy managing methods that make this approach unique and innovative.

In the second reporting period [8], QRDC was able to design, fabricate, and evaluate the key components of the SmartScreen™. The benefits of these prototypes were shown to be close to the predicted performance. They included: broader and finer control of the screening frequency, extremely low power consumption, tremendous reduction in operating noise level, and remarkable reduction in transmitted vibration from the screen to the supporting structure. The increased control over the motor frequency allowed QRDC's SmartScreens™ to be tuned for optimum operation and to be regularly changed to potentially avoid blockage or blinding of screens. Power consumption reduction allows for savings as well as increased potential number of screens to be in operation at one time. Noise and floor vibration level reductions improve worker safety as well as productivity. Additionally, reductions in vibration transmittance to the supporting structure potentially reduce floor vibrations, which may prevent interference in one screen's operation from another.

The third semi-annual report [9] shows the finalization process of the key components. that includes smart motor, resonator and supporting structure. It also details the assembly and evaluation of full SmartScreens™ system under laboratory conditions. This report also covers the details of Oscillating Mass (OM) driver to power full SmartScreens™ system and the lab test results.

The fourth semi-annual report [10] included detailed results of SmartScreens™ system test with modified supporting structure under dry and wet conditions. The lab test results of full system and vibration reduction on supporting structure was very encouraging. It also details the computer based analysis to further improve system performance in field installation and to reduce the stringent installation requirement. The report also included the results of a successful longevity test of smart motor using a quarter system while operating round the clock for over a year.

During this reporting period, significant work was done through experimentation and through computer simulations to minimize installation sensitivity and further improve system performance. Various suspensions were designed and tested both in lab and field. The lab and field test results showed significant performance improvement and less sensitivity to the installation. However system performance suffered during wet tests due to the effects of added damping. The motors did not have enough power to compensate for the losses and forced QRDC team to go back to the drawing table. There were two options, either to operate the system at a different mode which is less sensitive to external damping or to further improve system performance (overpower system) to compensate for the losses. Considering time constraints, it was decided to improve system performance. Through innovative isolation design and few other minor changes the system performance was almost doubled under lab conditions. This report also details the work done at Albany Research Center lab for strain measurement on the S3i-101 unit and the feasibility of using SmartScreens™ technology for dry application.

The ultimate goal of this project is to develop SmartScreens™ that will replace the inefficient massive electric motors. SmartScreens™ will have miniaturized, ceramic-based smart motors. SmartScreens™ will incorporate an energy management technique to control energy flow and will confine injected shaking energy to the screen panels. As part of the development efforts of SmartScreens™, a Steering Committee for Smart Screen Systems (SC-S3) was formed. Members of SC-S3 are QRDC (leading role), ARC (Albany Research Center, provide solutions that makes National's energy systems safe, efficient, and secure), U.S. Steel-MINNTAC (Minnesota ore operations), Ispat Inland Mining, S3i (Smart Screen System Inc.), and a representative of DOE-NETL. The QRDC team proposed to combine state-of-the-art smart materials, the concept of single or multi-stage resonators, and QRDC's recently patented energy management technique. This innovative technology has won several Research and Development awards from the U.S. Army, Navy, and Air Force and commercial organizations [2-4].

A miniaturized motor consumes 96% less energy than the bulky electrical motors and is capable of operating over a wide range of frequencies. These motors are almost maintenance free as they do not have any moving components and do not need lubrication. Piezoelectric ceramic material (Such as PMN= Lead Magnesium Niobate, and PZT=Lead Zirconate Titanate) can be miniaturized. Ceramic materials are well suited for applying large dynamic forces and the required shaking functions to resonators. In addition, ceramic materials will function as collocated sensors and actuators for active control of the shaking action and process automation. Cantilever resonators of appropriate shape and size will be used as resonators to amplify the displacements and accelerations so that the screening function is optimized. The combination of resonators and smart materials will offer full control and precision of the shaking function. Finally, the system will be optimized and completed by incorporating the energy management techniques that have been developed by QRDC. It is the combination of smart materials and the vibration energy managing method that makes the approach unique and innovative. Energy management is composed of energy diversion, confinement, dissipation, conversion, and cancellation.

The proposed technology offers significantly better energy management by controlling the flow of energy and confining it to screen panels rather than shaking the supporting frame, motor and surrounding structure. SmartScreens™ offers better control over the speed of operation, and type and magnitude of motion. These abilities help to quickly clean the screens and avoid blockage or blinding of screens. Use of miniaturized motors and by focused energy, SmartScreens™ eliminates and/or downsizes many of the structural components typically associated with industrial screens. As a result, the surface area of the screen increases for a given space envelope. This increase in usable screening surface area extends the life of the screens and reduces required maintenance. Energy management and better control of the screening process helps to remove particles of the correct size and thus increase the throughput, reduce material re-circulation, and significantly reduce in power consumption.

During last two quarters, we focused on reducing installation sensitivity and further performance improvement. Isolation mounts were designed to achieve the targets and were evaluated in lab and field conditions. Further refinements were done to the isolation mounts, resonators and motor installation to sustain system performance while operating in wet conditions. Lab tests are almost complete and the system will be evaluated in the field in coming days. During the last quarter an attempt was also made to investigate feasibility of inserting QRDC technology into a dry application.

This report summarizes the work since the last semi-annual report (Quarter 4-2004 & Quarter 1-2005) and has three main chapters. Chapter 1 is directed toward the lab and field testing of the refined system with isolation mounts. Chapter 2 gives summary of analytical simulation using finite element software. Chapter 3 gives details of a feasibility study of using SmartScreens™ technology for a dry application. A summary of findings, results, and recommendations are found in Chapter 4.

EXECUTIVE SUMMARY

Two undesired components of the material processing industry are excessive consumption of energy and extreme noise and vibration. Current screening machines use an electrical motor with a rotating unbalanced mass to generate shaking. These motors not only generate motion in the screen panels but also shake the supporting structures and other machines and structure in a plant. During initial field investigation of existing screening machines, it was found that the existing vibrating screens are inefficient, noisy and waste significant amounts of energy. Many areas were identified that need either improvement or complete changeover. These areas include, material handling, screening process, screen blinding, moving mass, motion, energy consumption, noise levels and vibration transmission, and workers safely.

To address the above-mentioned issues, QRDC proposed an innovative concept, SmartScreens™ technology, based on smart materials (miniaturized motors), and Energy Confinement and Flow Control. This project is jointly funded by the DOE and industry partners that include representatives of the mining industry ISPAT INLAND MINING, U.S. Steel-MINNTAC (Minnesota ore operations), QRDC (a technology company with an extensive relevant track record), S3i (screen manufacturing company transferring the prototypes to full marketable and producible products), and the Albany Research Center (provide solutions that makes national energy systems safe, efficient, and secure). The key objective of this project is to demonstrate the feasibility of energy management-based SmartScreens™ that can efficiently handle and process material separation. SmartScreens™ have the capability to control the flow of energy and confine this energy to the screen itself rather than shaking the entire machine and the surrounding structure, which comprises conventional vibratory screening machines. Better control of energy flow results in better screen recovery and reduced re-circulating load of the slurry. Single or multi-stage resonators with an advanced sensory system will be used to continuously monitor screening processes to improve productivity. Smart material-based miniaturized motors offer better control over speed of operation, and the type/magnitude of motion. These abilities help to effectively clean the screens and avoid blockage or blinding of the screens. Miniaturized motors eliminate any moving components such as bearings and bulky unbalanced rotating mass. This, in turn, virtually eliminates noise. With the proposed SmartScreens™ technology, the weight of the moving mass can be reduced by as much as 80%, and thus results in significant reduction in energy usage.

In the development efforts of SmartScreens™, baseline data was obtained and an initial field investigation was completed to identify problem areas in the current fine screens. Based on this information, a plan was developed that identified the basic design requirements to improve and efficiently handle the screening process. Various conceptual designs were identified for the key components of the system. These key component designs (i.e., smart motor and motion amplifiers or resonators) were modeled in CAD programs and analyzed through computer simulation and experimental tests. Some of the key component designs were selected and a full system was modeled that included the screen panel, four resonators, miniaturized smart motors, and the supporting structure for resonators and screen panel. The performance of these key components and systems was analyzed under various loading conditions through finite element analysis and experimental tests. Based on these results, three systems were selected. After a detailed review, one or two of these key components and systems were fabricated as a prototype for the SmartScreen™.

The PZT-based system performance was evaluated with isolation mounts to make system operation independent of installation. Extensive experimentation work was done both in lab and in field to optimize system performance while significantly reducing crosstalk between the mounting structure and the system. Stress levels and distribution on the S3i-101 unit experimentally evaluated using strain gages. Besides experimentation, finite element analysis of various key components was completed to further improve system performance. The longevity test of smart motor that was started in Sep-2003 is still ongoing and there are no signs of performance loss or failure.

During the next quarter we plan to test the system which is optimized in terms of performance and isolation in field under dry and wet conditions. The performance recorded so far is the highest ever recorded, exceeding twice the target performance. By the end of next quarter QRDC team expects to have a fully functional system based on PZT – Smart Motors. Parallel efforts will also be made to further extend the initial study in dry screening applications and come close to realizing a workable design concept that meets the requirements of the selected dry application.

The SmartScreens™ technology with its capabilities to reduce current energy requirement, maintenance cost in screening operations, improve throughput, and reduce noise and vibrations levels, can impact the global process industries. The widespread application of the proposed technology could change the way material separation is handled in general processing industries. Candidate industries are oil and gas, mineral processing, food processing, and pharmaceutical applications.

CHAPTER 1 – EXPERIMENTAL

As a continuation of the analytical work reported in last semi-annual report [10], experiments were conducted to evaluate the PZT based system performance while mounted on a suspension, and to validate finite element analysis results. For experimental testing purposes various suspension techniques were investigated including a test on SmartScreen™ 101 production unit as a quick solution. The details of each test, including PZT based suspended system evaluation, system refinement and optimization, full system strain measurement, and smart motor longevity test are presented in this section. To fully understand the content of this section, the reader is advised to review the previous reports [7-8-9-10].

1.1 PZT Based Suspended System

As mentioned earlier a system which is less sensitive to boundary condition (installation) should help improve overall system performance. The modified supporting structure did improve system rigidity and reduced undesirable supporting structure vibration [9]. However the plant structure could not provide required stiffness for the system to maintain its performance to the same levels as achieved at QRDC lab. To make system operation independent of installation, various isolation techniques were investigated. Figures (1.1.1) & (1.1.2) show the systems used and the following sections give details of the designs that were evaluated under dry and/or wet conditions.

1.1.1 Rubber Pads Beneath Supporting Structure

In this series of tests neoprene pads with three different durometers (10A, 30A, and 50A) were mounted beneath the solid leg system in attempt to isolate vibrations between the system and the floor. After the determination of the natural frequency of each configuration, the viability of each type of rubber was tested by measuring the stroke at resonance and phase between livedeck and supporting structure.

Table 1.1.1 depicts system performance measured at single point on the livedeck under the above mentioned conditions including baseline (fixed to the ground). It is very noticeable that the baseline case far outperforms any of the cases with isolation rubber.

Table 1.1.1 Vibration measurement on livedeck feed center under various conditions

Test Details	Operating Frequency [Hz]	Displacement [mils p-p]	
		Vertical	Horizontal
Baseline (fixed)	40.3	45	37
Neoprene – 10A	28.8	11	3
Neoprene – 10A	56.2	7	6
Neoprene – 30A	30.1	11	3
Neoprene – 30A	56.3	6	6
Neoprene – 50A	35.5	14	5

Neoprene – 50A	60	2	3

From the data gathered in this series of tests it was clear that simply placing rubber pads beneath the system will have adverse effects on system performance. The rubber however was certainly effective in isolating the machine from the ground. The results of this test lead the QRDC team to investigate other suspension designs for the PZT system.

1.1.2 Suspended System Using Strap Mounts

PZT based smart motors (total 4) were installed on production unit S3i-101 after few minor modifications to replace magnetic motors with smart motors. The moving mass (livedeck & panel) on a S3i-101 unit is suspended on straps and this configuration does a very fine job of minimizing vibration transmission to the floor. A PZT system with this suspension was evaluated under dry and wet conditions in the lab and in the field during this reporting period. First tests were conducted at Coleraine Mineral Lab (CMRL) followed by tests at S3i-Chisholm lab and Ispat-Inland mining plant. Refer Figure (1.1.3) and (1.1.4) respectively for lab and field setup of the S3i-101 with smart motors.

Table 1.1.2 Vibration measurement on livedeck feed center under dry & wet condition

Test Facility	Dry test			Wet test using taconite		
	Frequency [Hz]	Displacement [mils p-p]		Frequency [Hz]	Displacement [mils p-p]	
		Vertical	Horizontal		Vertical	Horizontal
CMRL	41.8	37	42	41.8	8	14
S3i-Lab	39.8	37	40	N/A	N/A	N/A
ISPAT	38.8	20*	25*	38.8	10	13

* System in operation was used and the screen was wet

Based on the above results it is clear that the system performed very well under dry conditions independent of plant structure. However under wet conditions the performance loss was significant and the motor's power could not be increased as they were running at their full capacity. System performance in the wet condition was not sufficient to meet screening requirement and this made the QRDC team to go back to drawing board.

Two possible solutions were discussed, to operate the system at a different mode which is less sensitive to external damping or to further improve system performance to compensate for the losses. Considering time constraints it was decided to go with improving system performance.

1.1.3 System Refinement for Performance Improvement

In order to maximize the performance of the PZT based S3i-101 unit, experiments were performed to identify the optimum location of smart motor/resonator interaction. Three force application locations were considered: nominal, raised 0.130", and raised 0.260". Changing the location to lower than nominal condition was deemed impractical because substantial machining of the set-up would have been necessary. The maximum height change was selected so that the contact location would remain on flat part of the resonator, thereby remaining perpendicular to the resonator surface. Height change was obtained by placing shims under the smart motor unit.

Stroke measurements were recorded at one corner of the live deck, on the static frame, and on the resonator itself with only one smart motor active. In addition, a load cell was placed inline with the PZT stack to measure the dynamic force created by the actuator. Since all corners were not active, these results are not to be interpreted in an absolute sense, but are to be used for comparison between shim thicknesses.

Test data shows that results of these changes create only small performance gains. It is clear, however, that if the locations on the resonator and live deck are looked at as a group, increasing the shim amount gives an overall improved result. The individual data points from all shim heights also generally form a trend. As the amount of force increases, the displacement drops. This trend is counterintuitive and further investigation into PZT performance was undertaken to better understand the phenomenon.

PZT Performance Modeling: An informal literature review was undertaken to better understand how PZT stacks perform in real world structures. Information was gathered from material available through vendors' websites and was supplemented with discussions with several knowledgeable vendor sources. The following summarizes the results of this research and some experimentation to verify the theories generated.

To begin, it is first necessary to define the two most important actuator characteristics. The "blocked force" is the maximum force and actuator can produce. The stack produces this force when the maximum allowable voltage is applied to the stack and displacement is constrained to zero. "Free displacement" is the opposite extreme: maximum displacement obtained by applying maximum voltage with no resistance to expansion. Another way to interpret these is as either the result of coupling the actuator to a system of infinite stiffness (blocked force) or zero stiffness (free displacement). Real world systems have some an intermediate stiffness so that some intermediate amount of force and displacement are achieved. Understanding this trend in a concrete way is the key to correctly sizing an actuator to meet desired performance specifications.

Actual performance of a given stack is affected by many other variables such as preload on the stack and hysteresis of the material. PZT actuator performance limits can be estimated as shown in the Figure 1.1.5. What follows is detail explanation of Figure 1.1.5. The endpoints of the line are formed by the stack characteristics while all realizable operating conditions fall somewhere roughly along the line. Displacements were measured on the resonator at the force input location and on the rear of the smart motor assembly. These results were combined to form the differential displacement across the PZT stack (indicated as points on the plot). A load cell was again used to monitor the dynamic force created by the stack. Different force levels were created by limiting the voltage applied to the PZT stack, allowing for the force/displacement characteristics of the system to be studied. The data supports the hypotheses in two ways. First, at the maximum allowable voltage of 200V, the system is performing near the predicted limits. Second, the force versus displacement data from all voltage levels forms a nearly linear curve which can be interpreted as the structure's stiffness at the frequency of operation. Work is underway to further validate these models. The various test conducted at QRDC lab on smart motors suggests that the PZT stacks are performing to their limits in the current configuration.

Use of Coil Springs: Current S3i-101 units employ an integral suspension system (straps) to help isolate the machine from the surrounding environment. Earlier structure design [10], refer to Figure (1.1.1), did not employ any isolation mechanism. So as a quick investigation, four coil springs were attached to the bottom of the structure as shown in Figure (1.1.6). Qualitative observations show that the isolation created by this suspension is very encouraging. Furthermore, much improved stroke levels were recorded. Table 1.1.3 shows a comparison between a S3i-101 unit with straps as suspension and the modified supporting structure with coil springs as the suspension. Smart motors were used for both cases and similar input conditions were maintained.

Table 1.1.3 Vibration measurement on livedeck feed center under lab condition

System Informaiton	Displacement [mils p-p]	
	Vertical	Horizontal
S3i-101 with straps suspension	41.1	44.4
Modified structure with coil springs	82.0	54.61

1.2 Full System Strain Measurement

Strain data was collected on a S3i-101 unit to evaluate the stress levels of critical parts and validate stress results from finite element model. To realize this goal QRDC approached The Department of Energy (DOE) Albany Research Center (ARC) for strain measurements. QRDC engineers worked with the scientist from ARC to setup the system and with the expertise of entire team, this task was completed successfully. This report briefly summarizes the process taken to measure and record strain data, ODS & stroke/acceleration data, as well as the process of correlating that data to the FEA model.

1.2.1 Strain Measurements

The strain gages used in this investigation are common foil type gages. These gages are created by bonding a very thin metal wire to a flexible substrate. This flexible substrate can then be bonded to the surface of a test object. As the structure changes shape, the wire is stretched or compressed, changing the wire's resistance. Figure 1.2.1 shows the side view of S3i-101 unit with strain gages.

1.2.2 ODS and Stroke/Acceleration Measurement

The purpose of measuring ODS and Stroke/Acceleration data is to ensure that the operating shape of the machine is known and the actual displacement it undergoes during operation can accurately be matched by the FEA model. This is one of the best means of ensuring the validity of comparing stresses in the tested machine to stresses in the model.

1.2.3 FEA to Test ODS and Stroke Correlation

The first step in comparing the results of the ODS and stroke measurements was to calibrate the FE model. This was done by varying the excitation level of the FE model until the predicted output at a selected point on the structure matched the experimentally measured response at that location. For all data points with substantial motion on the livedeck, the

FEA data matches the test data to a high degree of accuracy to within 15% in both vertical and horizontal direction. Figure 1.2.2 shows an experimental and FEA stroke comparison graph.

12.4 FEA to Test Stress Measurement Correlation

In order to compare the experimentally measured strain data and FE stress data, post-processing of the strain data was necessary. Matlab® software was used to post-process time domain strain data and convert it to Von Mises stress. For proper correlation of FE and test data, only steady-state data was taken into consideration throughout the analysis. Figure 1.2.3 shows a typical time trace data (full and shortened) on the resonator.

Equation (1) was used to transform the individual strain signals into the complementary principle stress time histories. These results were than used to calculate Von Mises stress using equation (2).

$$\sigma_{1,2} = \frac{E}{2(1-\upsilon)}(\varepsilon_A + \varepsilon_C) \pm \left[\frac{1}{2(1+\upsilon)}\right] \cdot \sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2 \cdot \varepsilon_B - \varepsilon_A - \varepsilon_C)^2} \qquad (1)$$

$$\sigma_V = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \qquad (2)$$

Figure 1.2.4 compares stress results of finite element model with that of experimental results. The graph shows a nearly identical trend in the stress data; however FE results tend to be higher. This make sense and was expected as the current FE model considers perfect conditions and does not take into consideration any losses at the various interface, which makes the system stiffer than the real world condition.

1.3 Smart Motor Longevity Test

The longevity test that was started on 8th September 2003 is still ongoing [10]. The PZT based smart motor has more than 565 million cycles. At the time of this report there are no signs of performance loss or any damage to the ceramic or any part of the assembly.

CHAPTER 2 – FEM ANALYSIS

In order to improve system performance various designs were analyzed either through resonator or interface modification. What follows in this chapter is a brief description of each design analysis and results summary.

2.1 Force Input Location Study

PZT system mounted on isolation spring was analyzed for best force input location. Input forces from PZT based smart motor were applied near the root of resonators and reaction forces were applied on the motor mounting block. The location of the force was gradually changed from 0.25” to 0.5” and finally to 0.75”.

Analysis Results: Performance of the system doubles with every increase in input force location from the root. At the same time, relative displacement between resonator and motor mounting block doubled. This represents the ceramic stroke. So the final conclusion of this analysis is that there is a tradeoff between ceramic stroke and force generated (blocking force) and this constraint dictates the best ceramic input force location. In the current case, this is 0.5” from the resonator root.

Table 2.1.1 below gives brief summary of analysis results. Panel displacement is measured along the feed side center & ceramic stroke is the relative displacement between resonator and motor mounting block.

Table 2.1.1 Screen performance at feed end center with different force input location

Motor location	Panel Displacement [mils p-p]		Ceramic Stroke [mils peak]	
	Vertical	Horizontal	Bet res & mt. block	Phase diff.
0.25”	7	22	0.5	Less than 1 deg
0.5”	17	56	1.4	Less than 1 deg
0.75”	30	105	2.6	Less than 1 deg

2.2 Resonator & Livedeck Interface Study

The performance of PZT system was analyzed with relaxed constraints on the top end of resonators. Various cases were analyzed that include rotation free constraints on all four resonators and two pinned and two clamped. The key objective of this study was to improve resonator life by reducing stress levels and improve system performance. To model rotation free joint or pin joint, a line coupling between livedeck and resonator top surface was used. To regain target mode frequency, resonator dimension were changed accordingly.

Analysis details: A PZT system with single-leaf resonator was used to evaluate the influence of relaxed constraints on resonator top surface. Two main cases were evaluated, one with rotation free (pinned joint) constraints on all four resonators top surface as shown in Figure (2.2.1) and second case with two resonators rigidly clamped and two resonators with pinned joint on top surface, shown in Figure (2.2.2). Input forces and reaction forces were applied on resonators and actuator mounting blocks respectively to represent PZT motor forces. For the above discussed cases the results were compared with the baseline model in two ways, one by matching average displacement by varying input force magnitude and second by matching target mode frequency by changing resonator dimensions.

By releasing rotation constraints on top of all four resonators, stress levels dropped by at least 50% and require much lower input forces for the same displacements as that of fixed resonators. However target mode frequency dropped significantly, to somewhere in the range of 30Hz. Raising the frequency through resonator modification with released rotation constraints showed some improvement in stress levels (between 10–20%) and slight improvement in system performance. Two pinned and two fixed resonators drop stress levels by 10% to 50%, depending on the boundary condition of resonator (i.e., a pinned resonator will have much lower stresses than a fixed resonator). However there will not be any significant change in system performance and target mode frequency dropped by less than 20Hz compared to fixed resonator system. The major concern however, is practicality of a pinned joint and the design requirements outweigh the potential improvement.

2.3 Influence of System CG

Influence of system center of gravity (CG) on moving mass (panel & livedeck) and resonator stresses was analyzed using PZT based system with new supporting structure (refer Figure 2.3.1). CG coordinates for the baseline model were identified and full system was solved for free and forced vibration. Various modified cases were than analyzed by changing coordinates of the CG.

Analysis details: During earlier vibration analysis of the PZT system, it was found that the current operating mode has different motion distribution at the lower and upper end of the panel in the vertical direction. This was also determined through experimentation. It was thought that system performance could be influenced while improving stress levels by moving the system's CG. For this reason CG of baseline model was obtained and various cases were analyzed by moving CG coordinates along flow direction. This was achieved by adding mass on one side of the structure. Modified cases did not improve system performance compared to baseline model and there was no significant change in stress levels and stress distribution on the resonator surfaces.

2.4 Three Resonator System

The performance of the smart screen system was analyzed with a set of three resonators in place of four, as shown in Figure (2.4.1). The key objective of this study was to reduce stress levels on resonator by releasing some of the rotation constraints and at the same time improving system performance. A baseline model with a set of four resonators was analyzed and the results were used to compare with the three resonator system.

Analysis details: For the three resonator system, the baseline model was modified at the feed end by moving one of the resonators to the center and removing the other. Free vibration of the three resonator system resulted in 47 Hz as the target mode frequency, a drop of 7 Hz from the baseline model. Figure (2.4.1) show the target mode shape of three resonator system. For dynamic analysis, forces were applied at two discharge end resonators for both baseline and modified case. The results for the three resonator system did not show any significant improvement in horizontal direction however vertical motion at discharge end improved by 50%.

CHAPTER 3 – DRY SCREENING APPLICATION

The Department of Energy (DOE) awarded one year contract extension to QRDC Inc. to investigate feasibility of using SmartScreen™ technology in dry screening application. During the first quarter, the QRDC team (with the help of S3i team) identified a product and application to initiate a feasibility study. To realize the goal, a laboratory sized grain cleaning and separation machine (Cimbria 101 unit) on loan from Cimbria-Brantly was investigated. What follows in this chapter is brief description of the machine, vibration measurements and design opportunities to insert SmartScreen™ technology identified by QRDC.

3.1 Cimbria 101 Description

This machine is used in the food processing industry for grain cleaning and separation. Figure 3.1.1 shows a picture of the machine and identifies some of the major components. The machine consists of six primary components:

- Machine Frame
- Shoe
- Screen Panels
- Shoe Actuation System
- Feeding System
- Air Handing System

The machine frame refers to the steel superstructure of the seed cleaner. The shoe is moving part of the machine which houses the screen panels. The shoe is constructed of a special type of plywood made to be moisture and insect resistant. It is suspended from the machine frame by four steel straps and has a pendulum like motion. Three screen panels can be placed in the shoe. Material flow is directed so that material passes over each screen in series. In wheat processing (the primary concern during this investigation) the top deck is used to remove large oversized particles. The second and third decks are used for near size separation. The shoe is actuated by motor and mechanical linkage consisting of a belt and pulley for speed reduction, eccentric masses, and a connecting rod. The speed of this is variable on the laboratory unit, but is often fixed in industrial applications. Material feed into the machine is controlled in two ways. A metering roller is motor driven, allowing for the speed to be changed. Also, the gap between the hopper and metering roll is variable. The air handling system is the most complex part of the design. It is used to pull light and fine particles out of the material flow. This is done at many places throughout the machine and is controlled by five independent controls. It is important to note that this machine is a laboratory sized machine. Production units feature two shoes so that the horizontal dynamic forces of shoe motion are canceled out while the vertical forces are doubled.

3.2 Vibration Measurement

The objectives of this task were: (1) to gather baseline vibration data for purpose of system dynamics characterization, (2) to outline recommendations for a proposal based on vibration results. Modal data and operating deflection shapes (ODS) were extracted on each individual panel and the shoe. Figure (3.2.1) shows a typical frequency response function (FRF) and Figure (3.2.2) shows ODS results for one of the panels (16/64 round panel; top lot in shoe). In case of shoe modal analysis, two cases were considered, first with the rigid link between the eccentric motor and shoe in place and then with the link removed, allowing the shoe to move freely on the supports. Figures (3.2.3) & (3.2.4) show the FRFs of these two cases. From ODS measurements it was observed that the motion of the shoe is dominated by the front-to-back direction (flow) and very little vertical motion is observed.

Stroke data was collected on multiple points of the 16 round top panel screen, 5 slot bottom panel screens, and shoe using the same measurement points used for modal and ODS data collection. Average results for individual components and the system as a whole are presented in Table 3.2.1.

Table 3.2.1 - Stroke data for Cimbria Seed Cleaner

Component	Side-to-Side [mil pp]	Front-to-Back [mil pp]	Vertical [mil pp]
5 Slot Bottom	42	1161	145
16 Round Top	87	1179	138
Shoe Right	24	1160	40
Shoe Left	43	1176	30
System [All pts avg]	49	1169	88

3.3 Design Opportunities for QRDC

After gaining working knowledge of the machine and detailed vibration measurements, the project team identified several opportunities where QRDC technologies could be applied to improve machine characteristics. These areas are discussed in the following sections.

3.3.1 Shoe Actuation System

Currently, the Cimbria 101 unit employs a 0.37 kW single phase AC motor to drive the shoe. The mechanical linkage between the shoe and the motor's output shaft is fairly complex, involving a connecting rod, a secondary shaft with eccentric masses, and finally a belt driven pulley. Figures 3.3.1 shows part of the mechanism, including the secondary shaft, eccentric masses, and connecting rod.

The first priority in implementing SmartScreen™ philosophy will be to remove the eccentric mass drive system. Due to the large stroke requirements, it seems that the application is better suited for a magnetic drive system, than a PZT based actuation of the overall shoe, although nothing should be ruled out at this stage. Even with a large stroke actuation system, a mechanical amplification will be needed to obtain the machine's current stroke levels. Another possibility could be a linear motor.

3.3.2 Screen Actuation System

Random impacts by many rubber balls are used to excite the screen surface, thereby preventing screen blinding. Without this, the 5/64 slotted screen became almost completely blinded within 2 minutes of steady state operation at QRDC (see Figure 3.3.2). The balls are contained in ball trays, which sit immediately below each screening surface. The rubber balls, each approximately 10g mass and 25mm diameter, rest between ridges in the tray. During operation, the balls bounce randomly around between the ridges and screen surface, knocking trapped particles out of the screen holes. Even with this system, some screen blinding has been observed. The blinding primarily occurs at two locations where a high ridge in the ball tray exists (see Figure 3.3.2). The purpose of these high ridges is to keep the balls spatially distributed by preventing ball movement between adjacent sections of the ball tray.

The design team feels that PZT actuators could be used to excite the screen surfaces. The advantages of this are numerous. First, the inertia of the shoe will be reduced by removal of the mass of the ball decks. This will reduce energy consumption and ultimately reduce energy transfer to the surrounding environment. Second, the shoe design can be simplified. Finally, pzt based screen actuation can allow for the screen input to be tailored, maintaining the deblinding characteristics while reducing the noise created by the ball impacts. Testing at QRDC revealed that the average operating sound pressure level (SPL) dropped by about 8 dB by simply removing the balls.

3.3.3 Shoe Mounting System

The shoe is suspended in the machine frame by four steel straps. Each strap measures 2 inches wide by 19 3/8 inches long by 1/8 inch thick. Essentially, the shoe swings in the fore/aft direction on these straps, without much lateral motion. Also, due to the long length of the straps, only a small vertical displacement is induced for a relatively large horizontal displacement. With the connecting rod of the motor drive system disconnected, the natural frequency of the fore/aft motion of the shoe is near 3 Hz. According to Cimbria, the ideal operating frequency for the system is around 290 rpm, or about 4.8 Hz.

A clear design opportunity will be to tune the shoe suspension so that the fore/aft shoe mode matches the desired frequency of operation. This should be an easy way to lower the energy consumption of the machine. The solution here could range from a simple design change of the existing straps to a complete redesign of the shoe mounting system so that a QRDC designed resonator system is employed. The solution implemented here is implicitly linked to design decisions regarding the shoe actuation mechanism.

3.3.4 Machine Isolation

Currently, the machine frame is simply bolted to the floor or steel superstructure. The shoe is directly attached to the machine frame with four steel straps. This provides almost no isolation of the dynamic loads created by shoe motion. The only isolation present is a rubber mount where connecting rod attaches to the shoe.

Investigation into improving the isolation between shoe and machine frame is warranted. Other proposed design improvements should already help to mitigate energy transfer problems by reducing the amount of energy used in sifting, but more isolation may be desirable.

CHAPTER 4 – CONCLUSION

In this report, our progress since the last semi-annual report was detailed. It was shown that during last two quarters significant work was done and the progress has been very encouraging. The PZT system with various isolation mount configurations (neoprene, straps and coil springs) were successfully tested in the lab and in the field, both in dry and wet conditions. Various studies and refinements were carried out to improve overall system performance and to overcome performance loss due to added external damping in the wet test. Longevity test of the PZT based quarter system with smart motor completed over one year of operating time. Test started on 8th September 2003 and since than driven continuously round the clock with more than 565 million cycles. Both smart motor and resonator did not show any signs of failure or performance loss and the test was very successful.

With the help and expertise of the scientist from Albany Research Center, we were able to successfully evaluate stress levels and distribution on the S3i-101 unit. The test data and the results were also used to validate finite element models by comparing stress results and overall vibration characteristics.

We made significant progress for feasibility study of using SmartScreens™ technology for dry screening application. Several design opportunities were identified that can be implemented in various levels of integration, from simple retrofit solutions to partial or complete redesign of existing dry screening machines.

Fabrication of minor components to isolation system from the mounting floor is underway. Further system refinements through experimentation are in progress. QRDC team expects to have a full functional system using PZT based Smart Motors before end of next quarter. Final field test are being planned and will be completed within next few months. Next report will include lab and field test results of the Smart Screen System based on Smart Motors. The report will also include progress on the feasibility study of using SmartScreens™ technology for dry screening application.

FIGURES

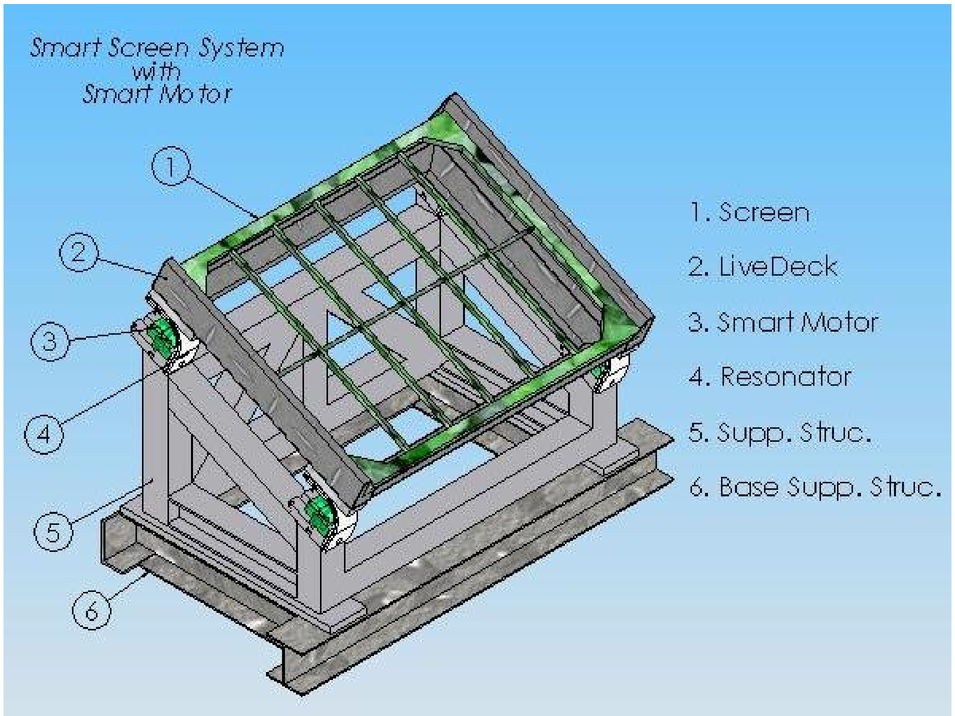


Figure 1.1.1 Model of SmartScreen™ system with modified supporting structure

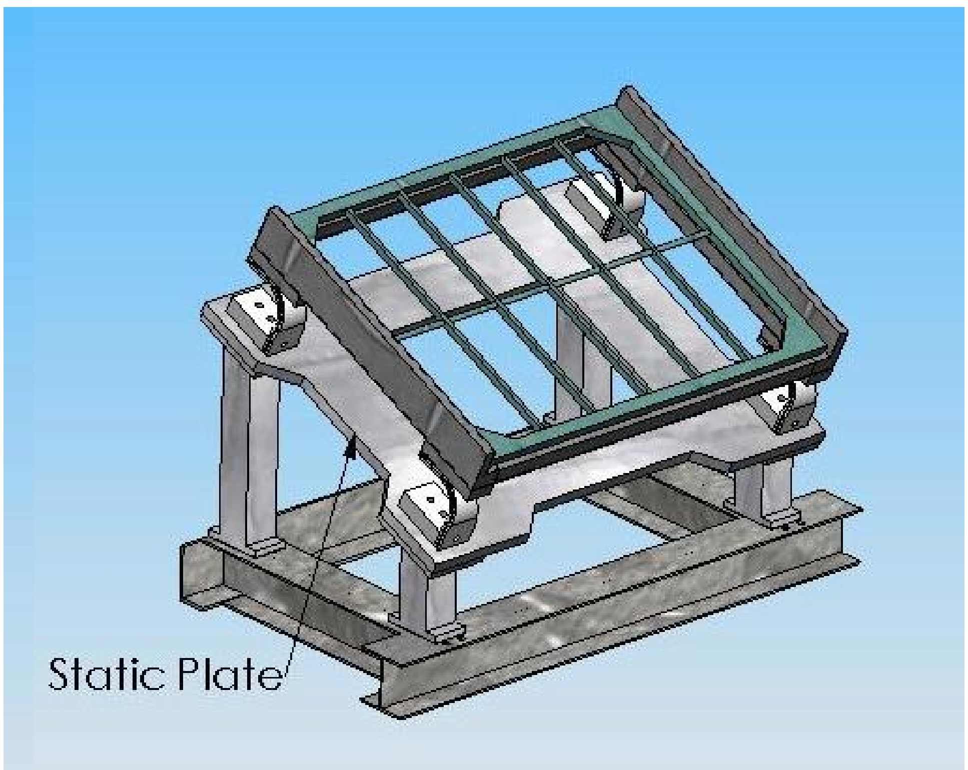


Figure 1.1.2 Model of SmartScreen™ system with old supporting structure

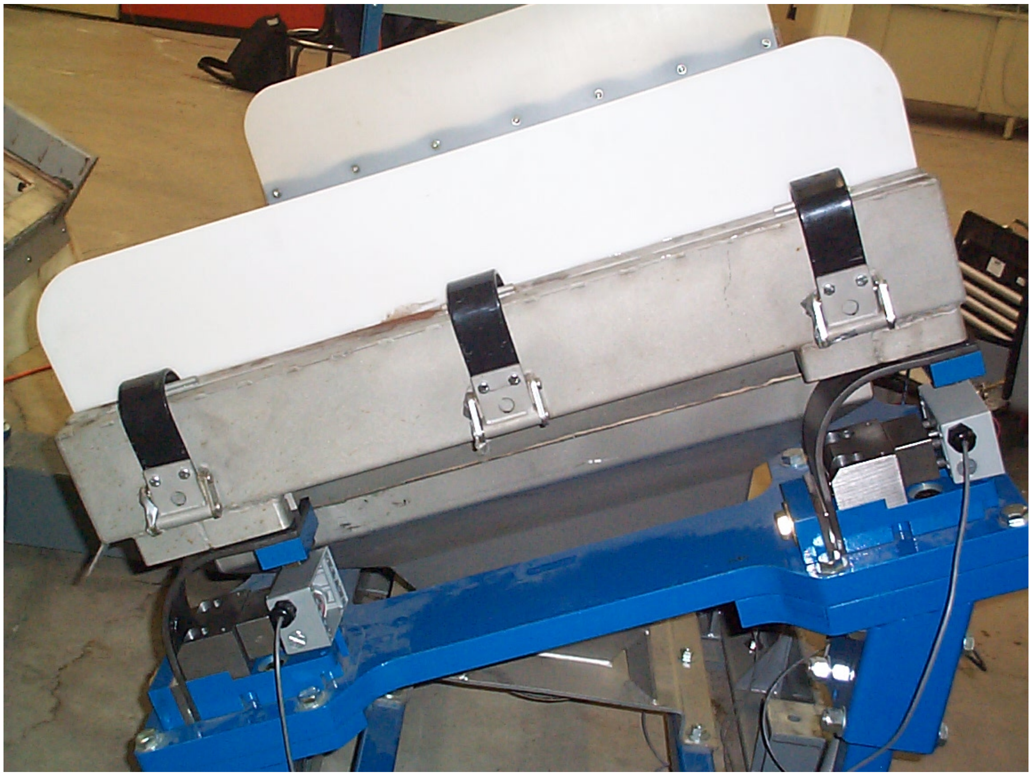


Figure 1.1.3 PZT system setup at S3i-Chisholm lab

Figure 1.1.4 PZT system setup at CMRL lab

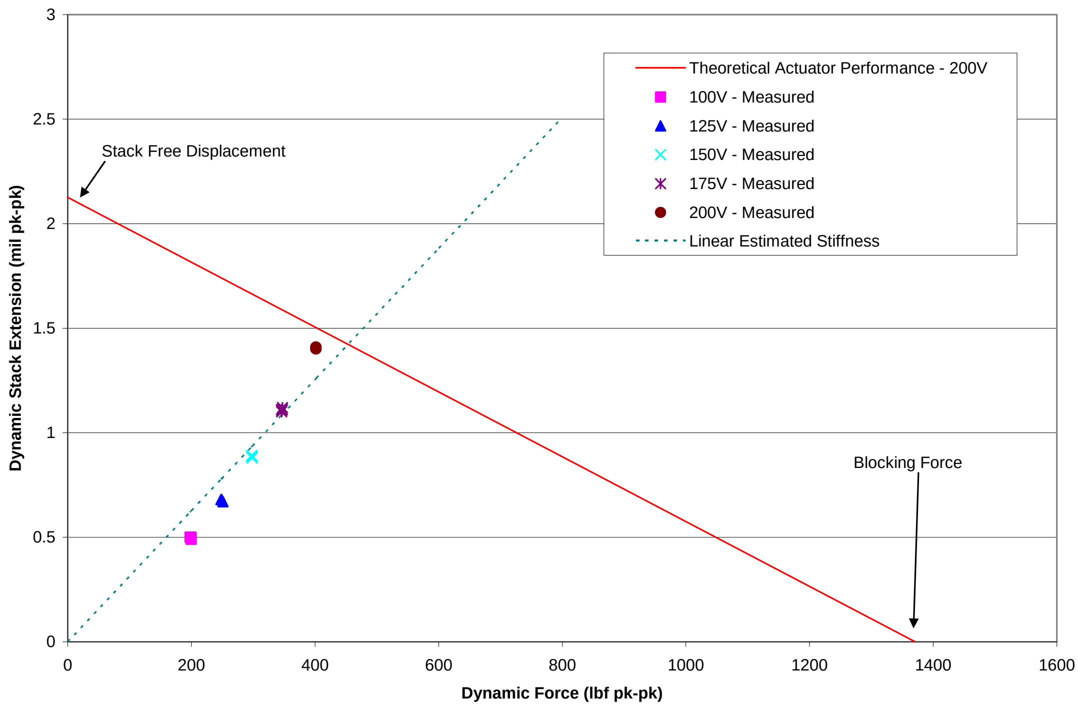


Figure 1.1.5 Actuator performance in S3i-101 system

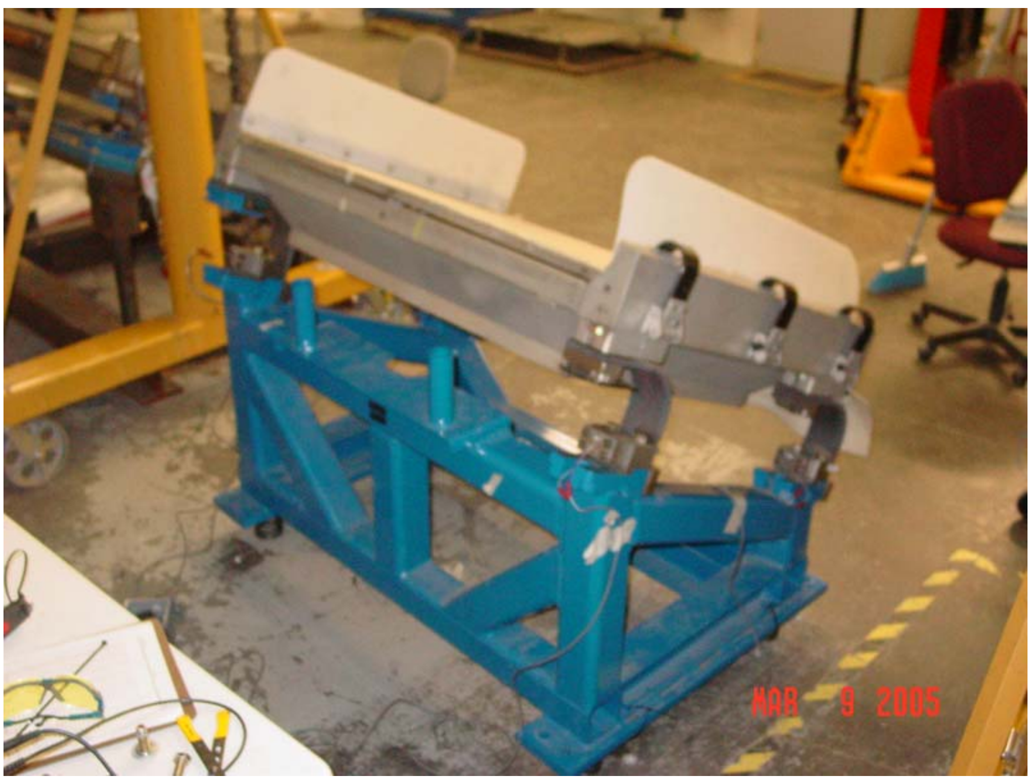


Figure 1.1.6 PZT based system mounted on coil springs at QRDC lab

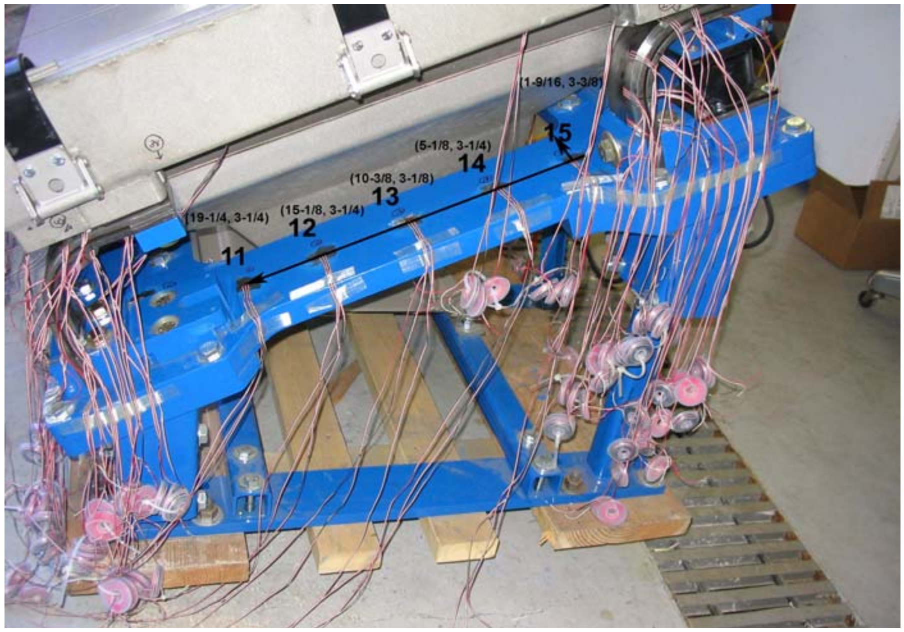
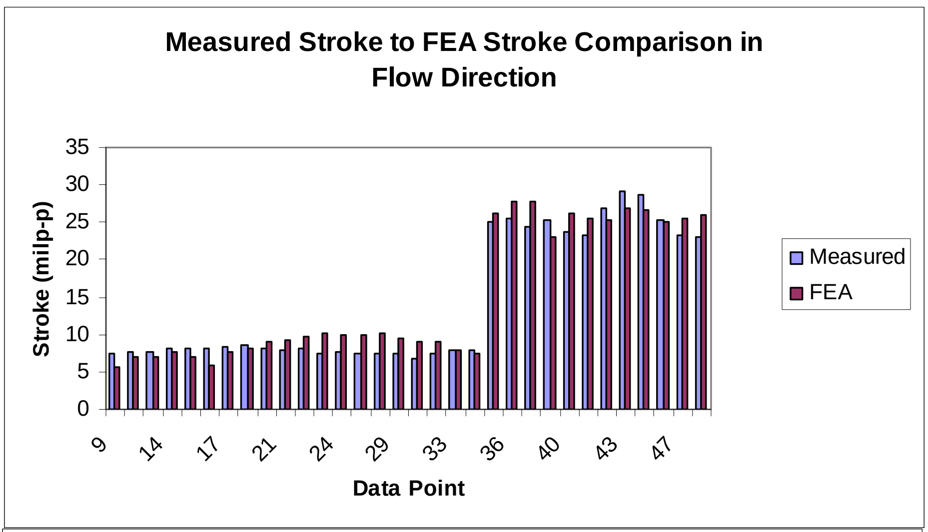


Figure 1.2.1 Side of S3i 101 with strain gages attached



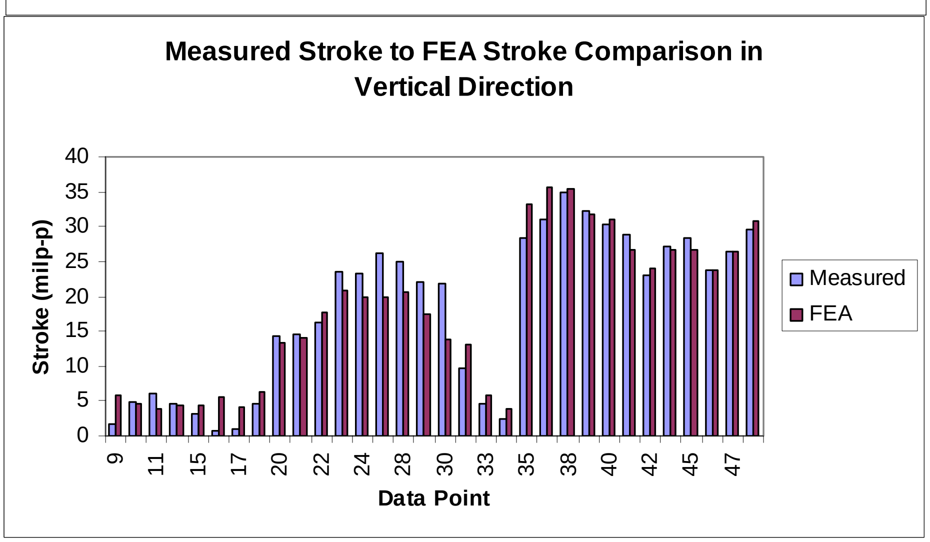


Figure 1.2.2 Stroke comparing (trend) between FEA and test data at various points on the system (Top: vertical direction, Bottom: flow direction)

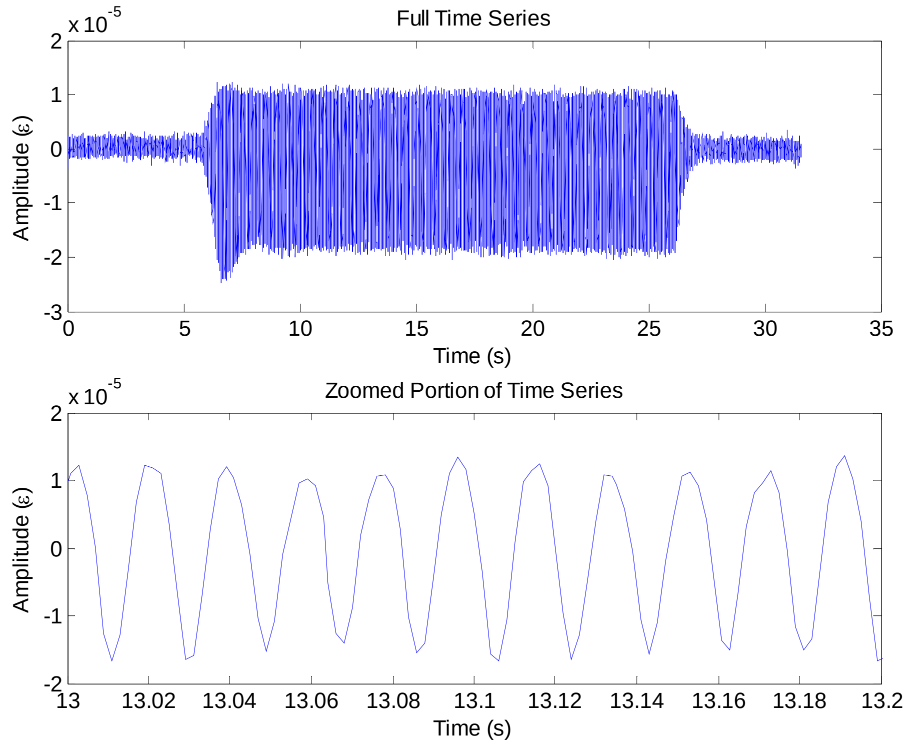


Figure 1.2.3 Time history from resonator strain gage

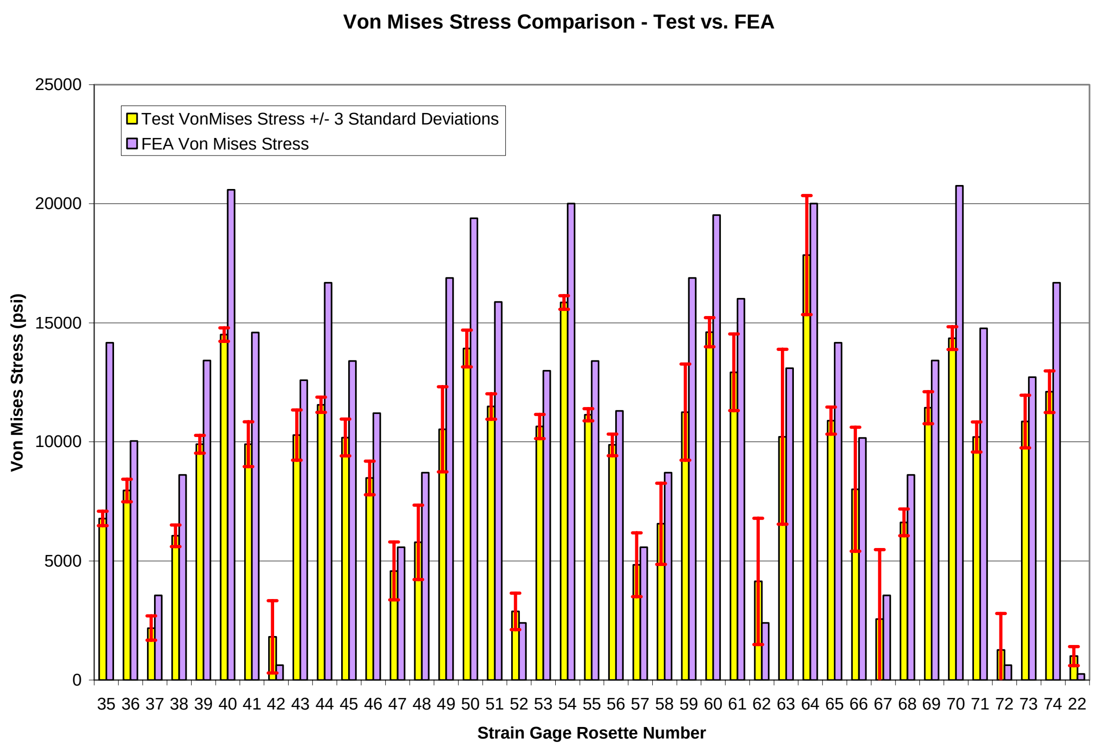


Figure 1.2.4 Test and FEA Von Mises stress comparison on resonator

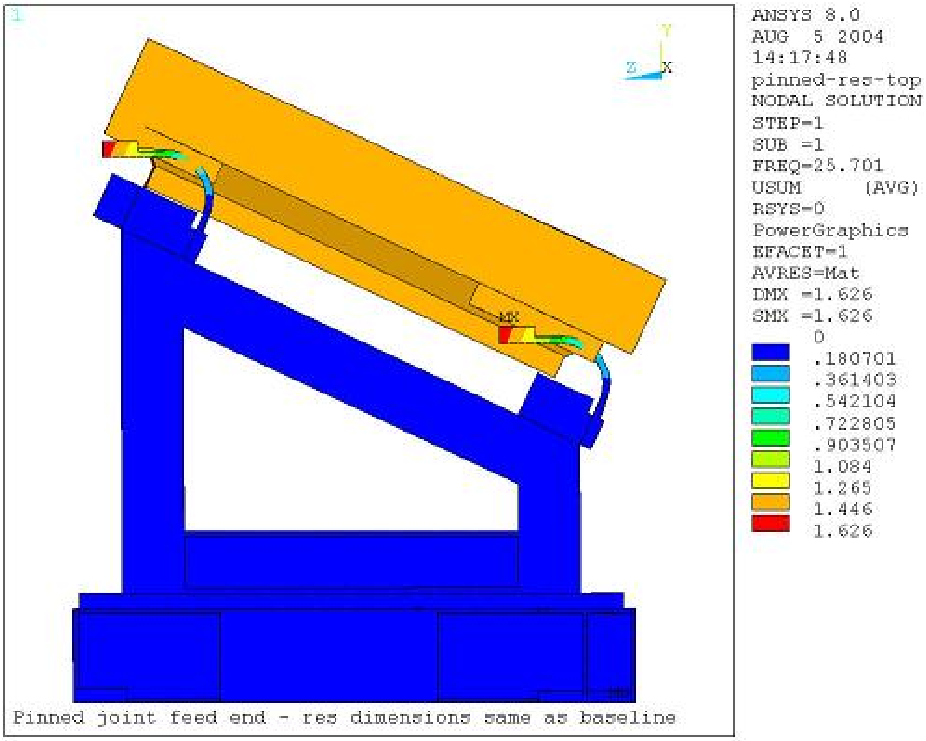


Figure 2.2.1 Rotation free top - target mode shape

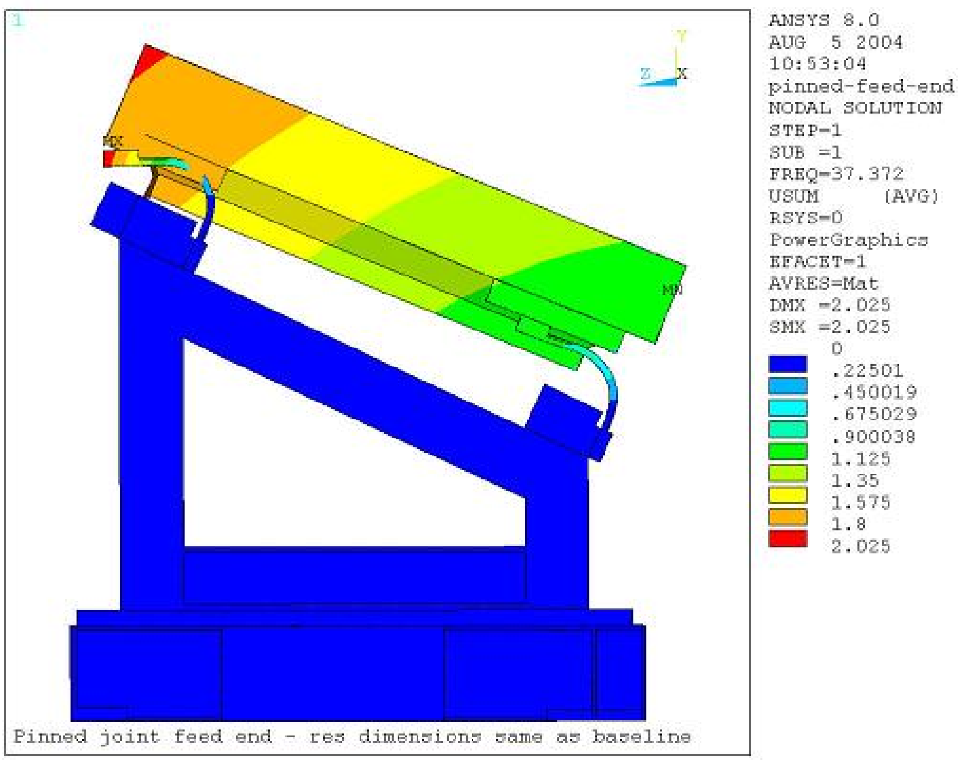


Figure 2.2.2 Pinned feed end - target mode shape

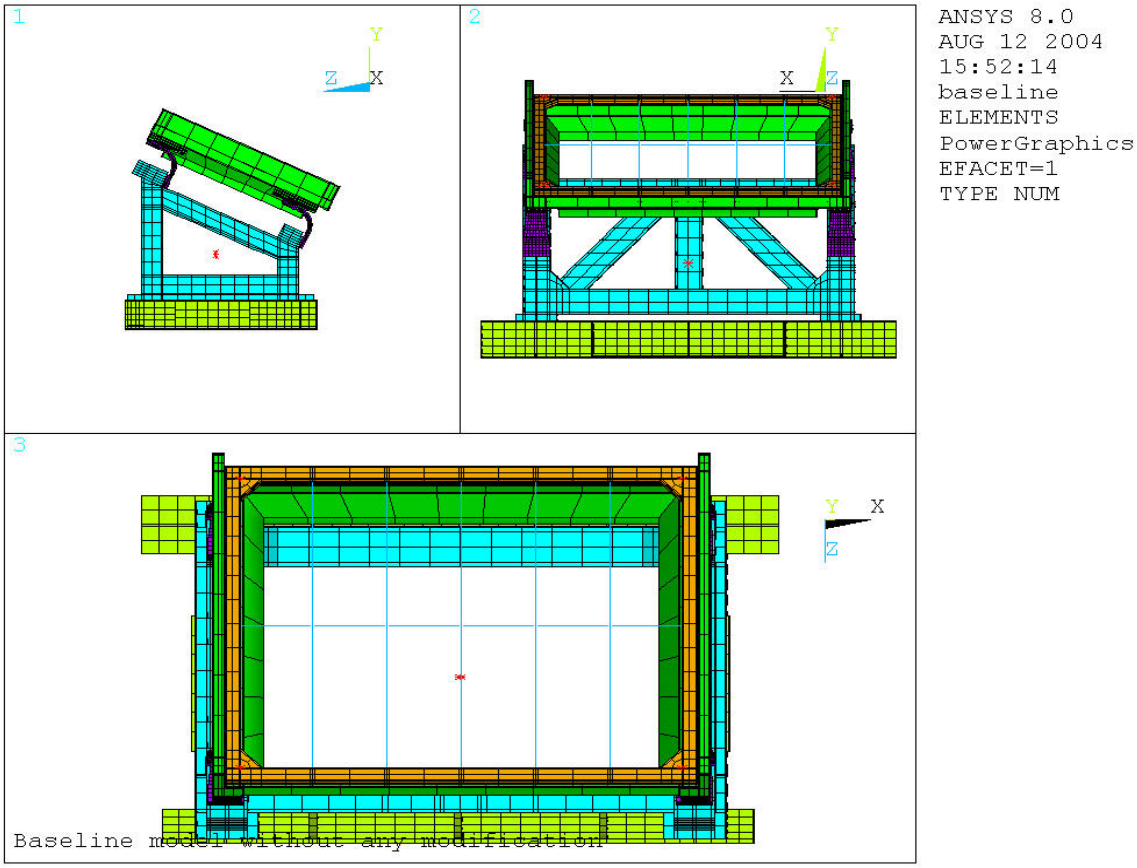


Figure 2.3.1 Baseline model center of gravity in different views

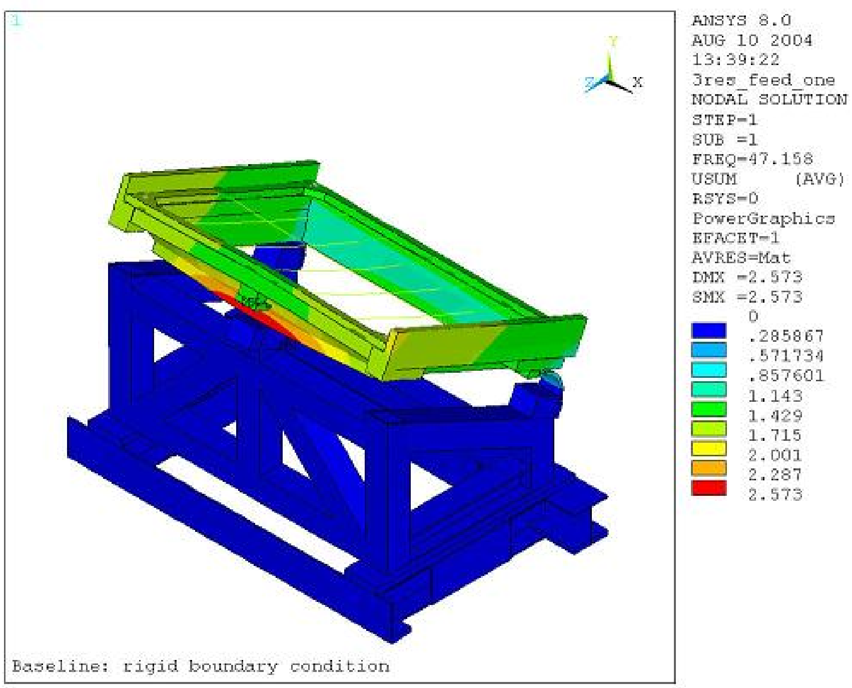


Figure 2.4.1 Modified three resonator system target mode shape

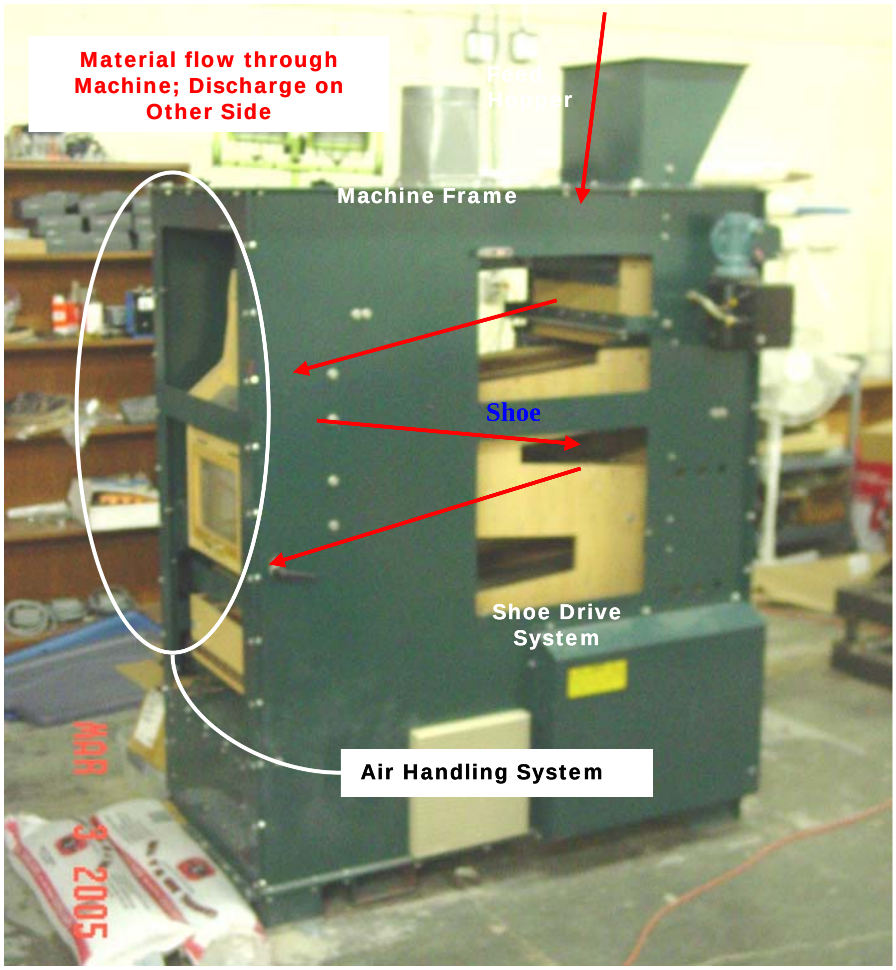


Figure 3.1.1 Cimbria machine installed at QRDC

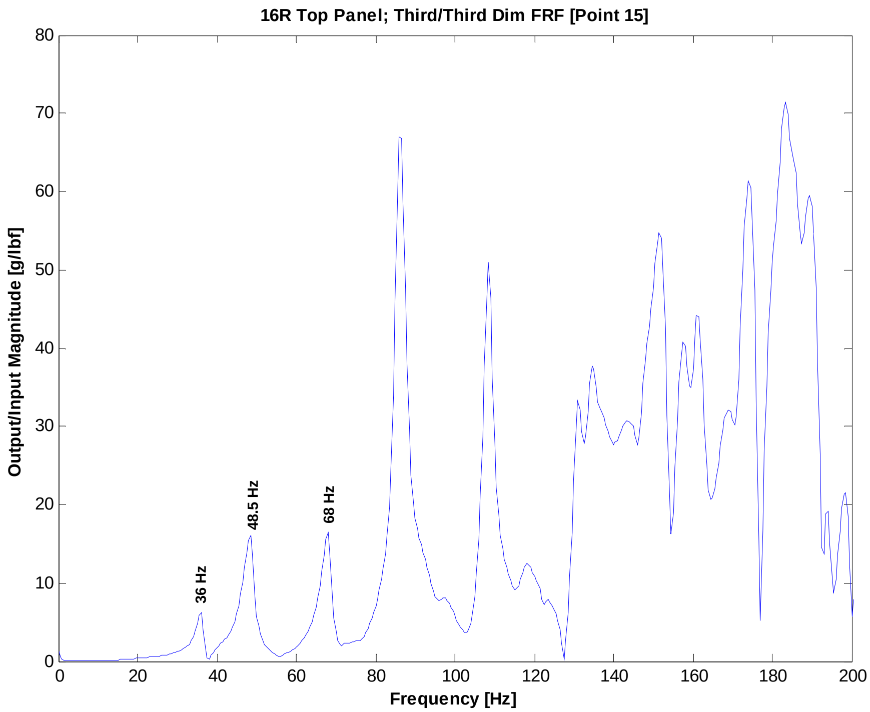
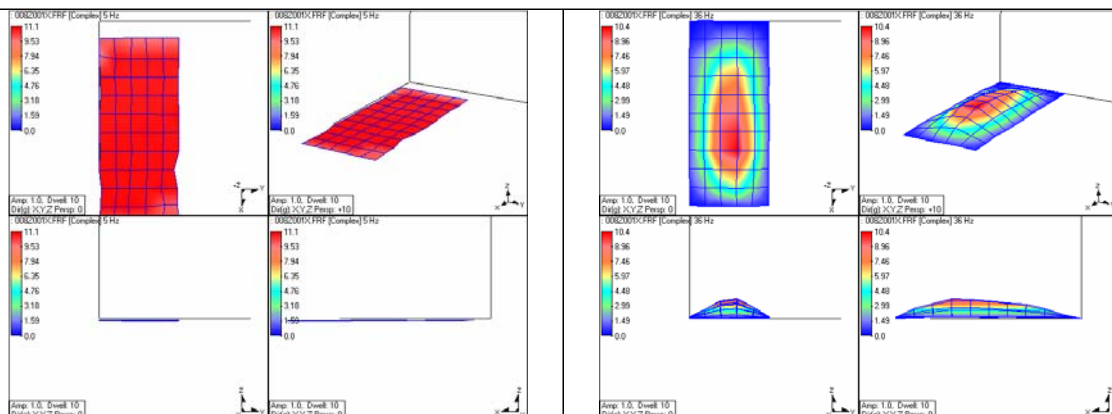


Figure 3.2.1 Frequency response function of 16R top panel



(a)

(b)

Figure 3.2.2 ODS of 16/64 round mounted in top tray, (a) ODS at frequency of operation 5 Hz, (b) ODS of response at 36 Hz.

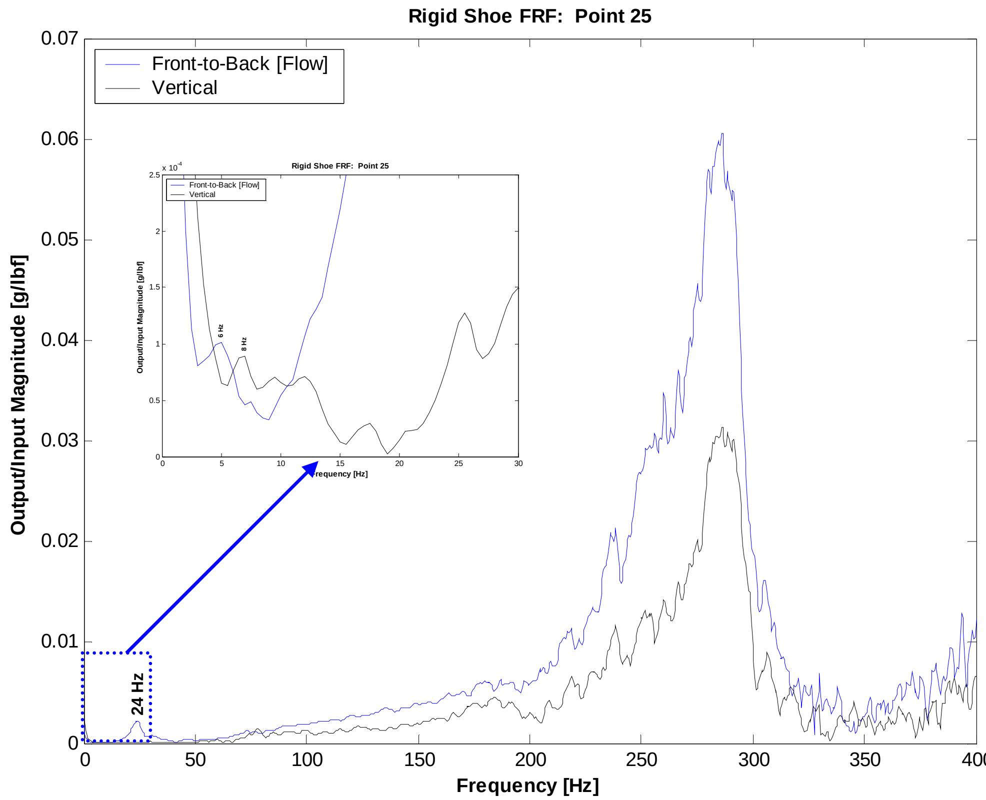


Figure 3.2.3 Rigid Shoe frequency response function at point 25, vertical and flow directions

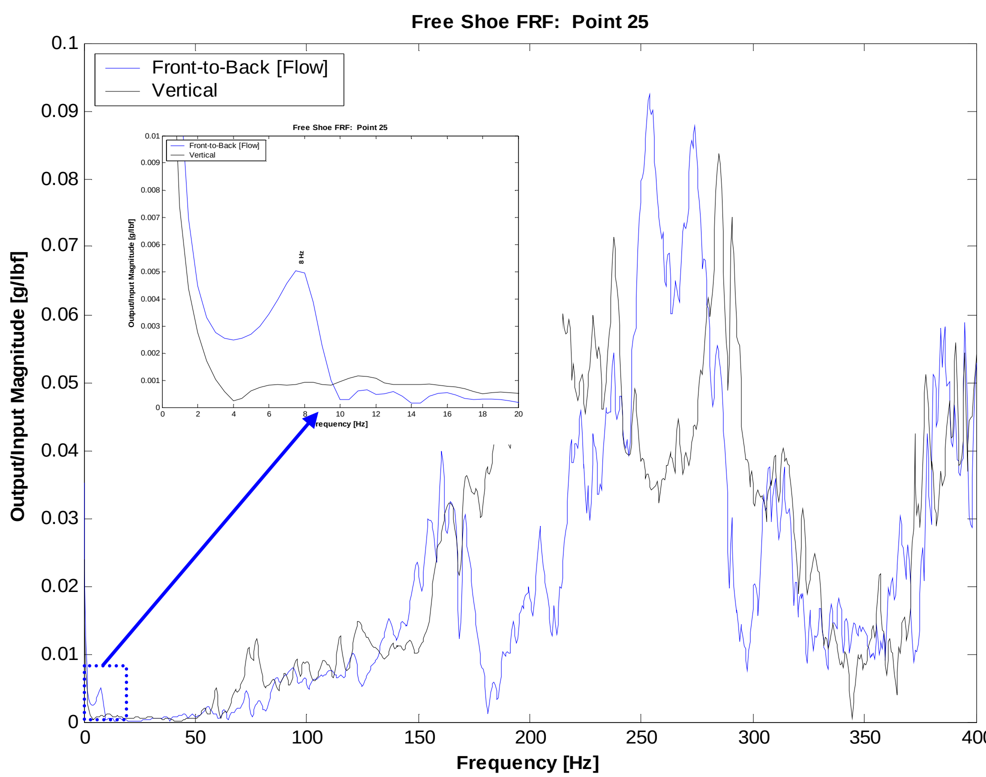


Figure 3.2.4 Free shoe frequency response function at point 25, vertical & flow directions

Figure 3.3.1 Shoe drive connecting rod

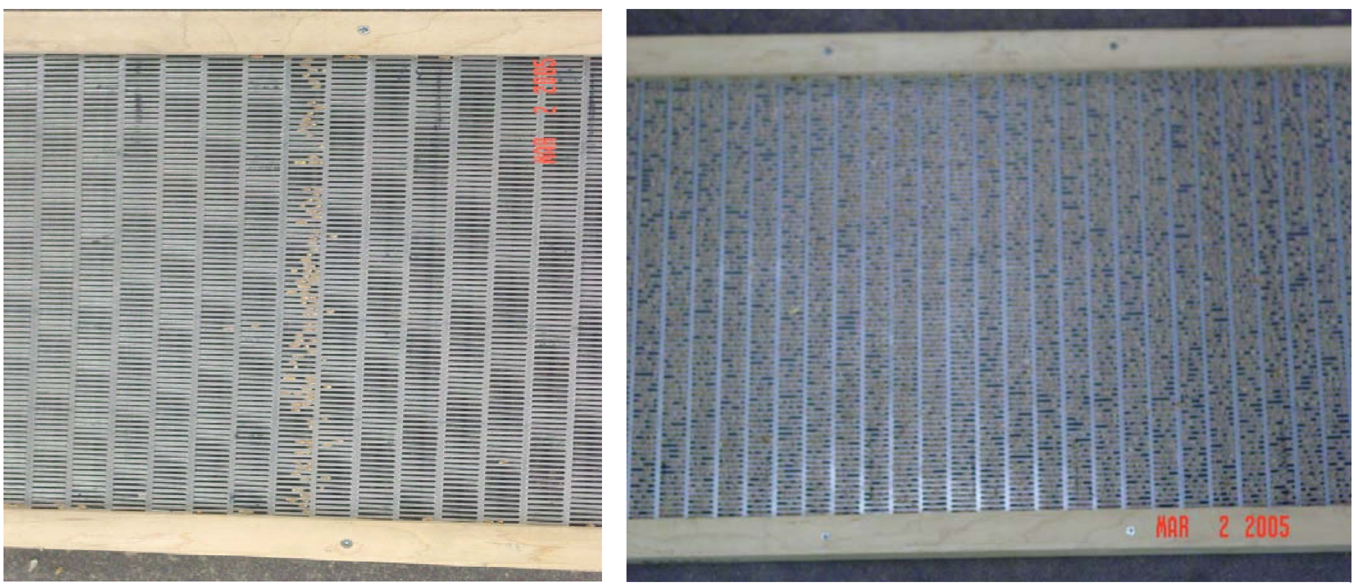


Figure 3.3.2 Screen after operation with (left) and without (right) ball deck

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LIST OF ABBREVIATIONS

S3 – Smart Screen Systems
ARC – Albany Research Center
SM – Smart Motor
SC-S3 – Steering Committee for Smart Screen Systems
PZT – Lead Zirconate Titanate
PMN – Lead Magnesium Niobate
CAD – Computer Aided Design
FEM – Finite Element Analysis
OMS – Operating Mode Shapes
MSHA – Mine Safety and Health Administration's
PLC – Programmable Logic Controller
SPL – Sound Pressure Level
OM – Oscillating Mass
LD – Live Deck
OMR – Oscillating Mass Resonator
CMRL – Coleraine Mineral Research Laboratory, part of The University of Minnesota
IIM – Ispat Inland Mining